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Stress Analysis of Hygrothermal Delamination of Quad Flat No-lead (QFN) Packages

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ABSTRACT

Interfacial delamination is the major reliability issue of Quad Flat No-lead (QFN) packages under the JEDEC-MSL preconditioning and reflow process. Failures will occur when the hygrothermal stress exceeds the interfacial strength. Questad[1] established an integrated stress model in order to onsider all the effects together. The thermo-mechanical, ygro-mechanical and vapor stress were calculated separately th lots of modeling techniques then integrated into one odel. However, the failure mechanism is still not clear since e critical interfacial stress was not discussed and the mulation result lacks experiment validation. Driel et al[2] so discussed the initiation of delamination in QFN using terfacial fracture mechanics. But the simulation result was ally dependent on the location and the length of the pre-ack. Therefore, the contribution to the failure of each effect eeds to be identified with more experiment validations.

To break the gap between FEA and experiment validations, complex system shown in Figure 1 is established to study the lure mechanism of hygrothermal delamination. Two kinds of ummy QFN packages with different lead-frame will be anufactured as the test vehicles for this study. The research ethodology generally divides into two routes. One follows the mulation route, starting from material characterization to ite element modeling. Strength approach is then applied to aluate the package reliability. In the other route, dummy FN are fabricated and tested to provide experiment result for ter comparison. The stress analysis with red background will e discussed in this paper, more details about the sample eparation and experiment tests with yellow background is troduced in reference[3]. The major objectives of this paper e given as follows:

A finite element model will be established to figure out the interfacial stress distribution along different interfaces when dummy QFN is subjected to the pure thermal loading and hygrothermal loading.

z Strength approach is applied to evaluate the package

Table 2. Material Properties for Thermo-mechanical Stress Analysis

Material	E (GPa)

paths, shear stress remained the dominant stress component with maximum value at point F about -1.7 MPa. Once the interfacial stress distributions were derived, the failure criterion can be described as follows:

$$D \quad [\frac{\tau}{S}] \qquad (3)$$

where τ means the shear stress from FEA calculation, S means the interfacial shear strength from mechanical tests seen in Table 3, D means the failure factors. The larger the value of D, the higher the possibility of failure. In this study, button shear and die shear tests were conducted to determined the interfacial shear strength. More details are presented in reference [8]. From the calculations of D listed in Table 4, some estimation could be given as follows:

- Compare the D in rows, point C has the highest value among all which means the delamination will initiate at molding compound/lead-frame interface around the junction of die attach fillet.
- Compare the D in columns, the values at point C in package 2 are higher than the ones in package 1 which means package 2 will have lower reliability against the interfacial delamination than package 1.

Table 3. Interfacial Shear Strength (MPa)

MC/Si	MC/ LF$_{Ag}$	MC/ LF$_{PPF}$	DA/ LF$_{Ag}$	DA/ LF$_{PPF}$
10.00	11.23	7.56	7.55	27.33

Table 4. Calculation of Failure Criterion Factors D

	1) MC/Si (A-B)		2) MC/LF (C-D)		3) DA/LF (E-F)	
	A	B	C	D	E	F
Maxi Shear Stress (MPa)	0	6.38	-13.82	-3.45	0	-1.70
Maxi Peeling Stress (MPa)	0	2.01	-6.23	-17.91	0	-3.50
$D_\tau = [\tau/S]$	0	0.64	1.23	0.31	0	0.22
$D_P = [\sigma/S]$	0	0.64	1.83	0.46	0	0.06

With the above expectations, the experiment validations were implemented following the test A in Figure 7. In order to apply the pure thermal effect to the packages, the dummy QFN went through reflow just after 24 hours baking without moisture preconditioning. Then the C-SAM inspections showed that package 1 could pass test A seen in Figure 8 when package 2 totally failed at this stage seen in Figure 9. From the C-Scan images in Figure 9, most of the outside boundaries of the delamination area (red area) pointing to the package edge were smaller than the inside ones. Combined with the delamination propagation trend we may conclude that delamination initiated at the molding compound/lead-frame interface around the junction of die attach fillet. The T-Scan images also reflected the C-Scan observations and confirmed the safety of die attach region beneath the die.

Figure 7. Flow Chart of Experiments using Dummy QFN

(a) C-Scan images

(b) T-Scan images

Figure 8. C-SAM Inspection of Package 1 after Test A

(a) C-Scan images

(b) T-Scan images

Figure 9. C-SAM Inspection of Package 2 after Test A

HYGRO-MECHANICAL STRESS ANALYSIS

In this study, the transient moisture diffusion and the subsequent hygro-mechanical stress modeling was performed using the coupled thermal stress analysis provided in the software. First the transient moisture field during reflow is derived then the swelling stress can be calculated with this moisture field. The governing equation of moisture diffusion is described by Fick's law as:

$$\frac{\partial C}{\partial t} = D_m \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right) \qquad (4)$$

where C is the moisture concentration, x, y, z are the spatial coordinates, D_m is the diffusivity and t is the time. However, the moisture concentration is not continuous at the interface. To avoid this problem, wetness approach [5] is applied here as:

$$w = \frac{C}{C_{sat}}, \qquad 1 \ge w \ge 0 \tag{5}$$

where C_{sat} is the saturated moisture concentration, w is the wetness fraction. Here, w=0 means dry and w=1 means fully wet. Then Eq. (4) turns into:

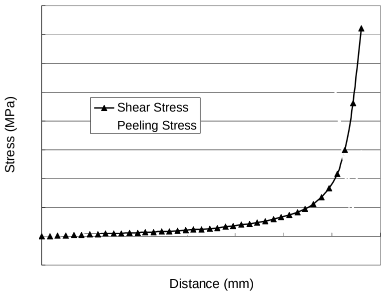
$$\frac{\partial w}{\partial t} = \mathcal{D}_m \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \tag{6}$$

where $\mathcal{D}_m = D_m * C_{sat}$, D_m is the coefficient of moisture diffusion. Then Eq. (6) could be solved using a thermal element type in ANSYS code.

For moisture absorption modeling, the initial condition is w=0 for the whole package, and boundary condition is w=1 at the external surfaces which are exposed to the ambient moisture. Unfortunately, the moisture material properties are not usually provided from the material supplier due to the complex sample preparation and time consuming moisture

INTEGRATED STRESS ANALYSIS

In MSL-3 test, the packages are subjected to hygrothermal effect during reflow. Both CTE and CME mismatch can induce the stress existing in the package. Therefore, an integrated



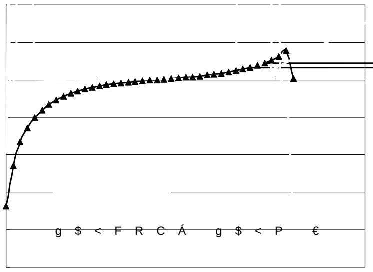


Table 6: Calculation of Integrated Failure Criterion Factors D

	1) MC/Si (A-B)		2) MC/LF (C-D)		3) DA/LF (E-F)	
	A	B	C	D	E	F
Maxi Shear Stress (MPa)	0	7.20	-16.87	3.92	0	-1.81
Maxi Peeling Stress (MPa)	0	2.94	-9.55	-18.98	0	-3.61
D_A =[2S]	0	0.72	1.50	0.35	0	0.24
D_P =[2S]	0	0.72	2.23	0.52	0	0.07

Now, the experiment validations were implemented following the test B in Figure 7. The dummy QFN went through reflow after 40 hours accelerated MSL-3 preconditioning following JEDEC standard[7]. The C-SAM inspections in Figures 16 and 17 showed that both package 1 and 2 failed at this time. Terrible delamination was found at molding compound/lead-frame and molding compound/Si(die top) interfaces. Focusing on the molding compound/lead-frame interface, most of the outside boundaries of the delam area pointing to the package edge were smaller than the inside ones. Considering the observations of the delamination propagation trend, most of the delamination was believed to be initiated at the junction of die attach fillet. This could be matched with the above estimation. Focusing on the molding compound/Si(die top), delamination were generated the edge of the die. This matched with the calculation of failure factors D along path 1 (A-B). Since point B had the higher value, it would be the initiation when delamination occurred at this interface.

Cross-sections of the failed sample after test B were photographed under Scanning Electronic Microscope (SEM). From the SEM images shown in Figure 18, the obvious crack tips have been observed. Both of them pointed to the die attach region, which proved that the delamination were initiated at MC/LF interface. Also, the thickness of the crack in package 2 is much thicker than that in package 1. This is reasonable because package 2 may already fail under the pure thermal effect. That reveals the delamination may be initiated earlier in package 2 and then the vapor pressure may take effect at a longer time on the delaminated surface. Therefore, the delamination opening could be larger in Package 2 due to the vapor pressure effect.

(a) C-Scan images

(b) T-Scan images

Figure 16. C-SAM Inspection of Package 1 after Test B

(a) C-Scan images

(b) T-Scan images

Figure 17. C-SAM Inspection of Package 2 after Test B

(a) Package 1 with Ag lead-frame

(b) Package 2 with PPF lead-frame

Figure 18. Cross-section Analysis of Dummy QFN after Test B

DISCUSSION

Fracture mechanics approach is another popular method to predict the delamination by comparing the stress intensity factor (K) or energy release rate (G) at different locations seen in references [1]-[2] and [10]. In order to derive the K or G, a pre-crack is embedded in the finite element model. However, the finite element model with an embedded pre-crack is different with the real situation where the sample is intact before reflow. Therefore, the fracture mechanics approach has some inborn defects to predict the delamination initiation. Also, the simulation results of fracture mechanics method are really dependent on the location and the length of the artificial pre-